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Blood flow velocity in the Popliteal Vein using Transverse Oscillation Ultrasound

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ABSTRACT

Chronic venous disease is a common condition leading to varicose veins, leg edema, post-thrombotic syndrome and venous ulcerations. Ultrasound (US) is the main modality for examination of venous disease. Color Doppler and occasionally spectral Doppler US (SDUS) are used for evaluation of the venous flow. Peak velocities measured by SDUS are rarely used in a clinical setting for evaluating chronic venous disease due to inadequate reproducibility mainly caused by the angle dependency of the estimate. However, estimations of blood velocities are of importance in characterizing venous disease. Transverse Oscillation US (TOUS), a non-invasive angle independent method, has been implemented on a commercial scanner. TOUS's advantage compared to SDUS is a more elaborate visualization of complex flow. The aim of this study was to evaluate, whether TOUS perform equal to SDUS for recording velocities in the veins of the lower limbs. Four volunteers were recruited for the study. A standardized flow was provoked with a cuff compression-decompression system placed around the lower leg. The average peak velocity in the popliteal vein of the four volunteers was 151.5 cm/s for SDUS and 105.9 cm/s for TOUS ($p < 0.001$). The average of the peak velocity standard deviations (SD) were 17.0 cm/s for SDUS and 13.1 cm/s for TOUS ($p < 0.005$). The study indicates that TOUS estimates lower peak velocity with improved SD when compared to SDUS. TOUS may be a tool for evaluation of venous disease providing quantitative measures for the evaluation of venous blood flow.

Keywords: Ultrasonography, Doppler ultrasonography, blood flow velocity, veins, venous flow, Popliteal Vein, Transverse Oscillation, Vector Flow Imaging.

1. INTRODUCTION & MOTIVATION

Chronic venous disease (CVD) is an umbrella term spanning venous disorders and affects a quarter of the adult population¹. CVD presents with symptoms and signs like leg pain, skin changes and venous ulcerations and is defined as “morphological or functional abnormality of the venous system of long duration”^{2,3}. The main diseases of the veins in the lower limbs are varicose veins, deep venous thrombosis and post-thrombotic syndrome. Varicose veins are mainly caused by venous valve incompetence but can also be due to occlusions in the veins of the lower limbs, the iliac veins and/or the inferior vena cava⁴.

CVD is evaluated with Doppler ultrasound (US) (color Doppler and spectral Doppler US (SDUS)) in a clinical setting⁵. Likewise, can obstruction be assessed by lack of flow with Doppler US. If obstruction is suspected further imaging examinations are warranted i.e. computed tomography venography (CTV), magnetic resonance venography (MRV) and iodine contrast phlebography. Intravenous ultrasound (IVUS) is an infrequently used method in this context. All these can assess the grade of flow restrictions based on anatomical criteria i.e. the maximal degree of narrowing⁶. CTV, MRV and phlebography can all define vein morphology and flow characteristics when restricted flow is suspected especially in the pelvic or abdominal veins⁷⁻⁹. The ancient phlebography and the IVUS techniques are complementary used for preplanning endovascular venous interventions¹⁰⁻¹².

Doppler US, the standard imaging method for imaging CVD, is associated with uncertainty due to the compressibility of the veins, and that the estimates are reliant on a beam-flow-angle between 45-60 degrees^{4,13-16}.

Transverse Oscillation US (TOUS) is an angle independent method for estimation of blood flow, introduced by Jensen and Munk^{17,18}. Complex flow is more elaborately visualized with TOUS compared to SDUS which is an advantage of the technique. The method has been assessed in different regions such as, the portal vein, the ascending aorta and arteriovenous fistulas for hemodialysis¹⁹⁻²². Venous flow in lower limbs has only been characterized with vector velocity US in a single report using plane wave imaging with an experimental scanner²³.

In this study we evaluated the antegrade flow in the popliteal vein of healthy volunteers using TOUS. The aim was to evaluate whether TOUS performs equal to SDUS for recording velocities in the veins of the lower limbs.

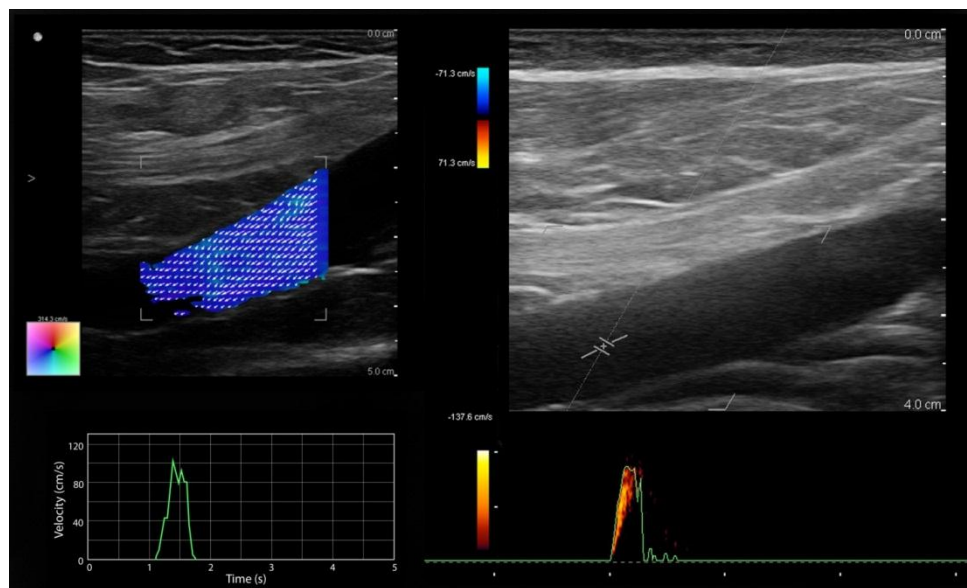


Figure 1: (left) Longitudinal scan of the popliteal vein with the TOUS method demonstrating a venous flow pulse. The direction and velocity of the venous blood flow are visualized with arrows superimposed on a color map. (right) Longitudinal scan of the same popliteal vein with conventional SDUS. A range-gate is placed centrally in the vessel and angle correction is applied. The peak velocities are shown for both techniques in the bottom of the figure.

2. METHOD

Four healthy male volunteers (1: 30 years, 2: 32 years, 3: 32 years, 4: 27 years) were evaluated with SDUS and TOUS (Fig. 1). The study was approved by the Danish National Committee on Biomedical Research Ethics and the local Ethics Committee (H-1-2014-FSP-072), and the volunteers were included into the study after informed consent.

The SDUS and TOUS measurements were performed with the same commercial ultrasound scanner (BK3000, BK-Medical, Herlev, Denmark) using a linear transducer (10L2w Wide Linear, BK-Medical, Herlev, Denmark). A cuff compression-decompression system was applied to the leg according to a set-up described by van Bemmelen et al. and replicated by others to make sure the blood flow of the veins was standardized²⁴⁻²⁶ (Fig. 2).

2.1 Spectral Doppler ultrasound

SDUS is the conventional way of measuring blood flow velocities with US. Pulsating signals are emitted from the transducer and consecutive received echoes are compared for blood flow velocity calculations. Doppler US is angle-dependent because the velocities are estimated in the axial direction in regard to the propagation of the sound waves i.e. the direction towards and away from the transducer. The technique does not estimate the velocities in the transverse direction i.e. the direction parallel to the transducer. The angle of insonation i.e. the angle between the sound waves and the flow of the blood, can be reduced by manually angulating the transducer, which may compress the veins or by electronically changing the angle of the emitted sound-wave, which is only possible when scanning with linear transducers²⁷.

2.2 Transverse Oscillation ultrasound

Jensen and Munk have introduced TOUS, which is an angle-independent method for estimation of blood flow^{17,18}. With TOUS it is possible to record the velocities of the blood in the axial as well as the transverse direction. The blood velocity in the axial direction is found as in conventional Doppler US. The blood velocity in the transverse direction is found by changing the apodization of the receiving elements and using a special estimator. The blood flow is visualized in a color-box and the pixels are color-coded to demonstrate the direction and velocity. The flow is easily interpreted with TOUS, as arrows are superimposed on the color-box, whereby the interpretation of the video-sequence is facilitated (Fig. 1)²⁷.



Figure 2: (left) The experimental set-up with ultrasound examination of the right popliteal vein while the right leg is unsupported and the lower leg is compressed with (right) a cuff compression-decompression system.

2.3 The examination set-up

With a cuff compression-decompression system (Rapid Cuff Inflation System, Hokanson, Bellevue, WA, USA), a single flow pulse was generated in the popliteal vein and measurements were performed at the same time. The cuff compression-decompression system consists of an air source (AG101), a rapid cuff inflator (E20) including output tubing, a 3-second timer and a foot switch. The output tubing was connected to a 13 x 85 cm cuff (SC12D) which was applied to the leg. The 3-second timer was customized at the Technical University of Denmark to enable activation of the system by the foot switch. The modification was necessary for a single operator to do the measurements.

Before each measurement the volunteer was standing on the opposite leg than the one examined. The examined leg was unsupported for one minute prior to the recording of the flow pulse to compensate for the venous refill time²⁵. Intervals of 1 minute was used between recordings, because this is the time it takes for the venous system to refill according to studies done with plethysmography²⁸. Each volunteer had 10 measurements of the right popliteal vein done with each technique. Between each measurement, the transducer was lifted from the skin of the volunteer and the settings of the ultrasound scanner were optimized.

Video files were extracted from the US scanner and used to calculate the TOUS peak velocities off-line using MATLAB (MathWorks, Natick, MA, USA) with an in-house developed script¹⁹. 110 vector velocity frames corresponding to 5 seconds of data acquisition were used for the velocity estimations. Each video sequence visualized a single venous pulse. Using conventional SDUS, the peak velocities were read off-line from screenshots of spectrograms each visualizing a single venous flow pulse, using a professional vector graphics editor (Inkscape, C/O Software Freedom Conservancy, Brooklyn, NY, USA).

2.4 Statistics

The descriptive statistics on the contained data for the four volunteers are given in Table 1. The average of the peak velocities and the average of the standard deviations were calculated for the four volunteers using both techniques. The peak velocities were analyzed with Bland-Altman plot and two-tailed paired t-tests, where $p < 0.05$ was considered statistical significant. Microsoft Excel (Redmond, WA, USA) and MATLAB (MathWorks, Natick, MA, USA) were used for the statistics.

3. RESULTS

The compared peak velocities are illustrated with Bland-Altman plot in Fig. 3. The mean difference is 45.56 cm/s and the limits of agreements are -32.83 and 126.93. The average peak velocities were 151.51 cm/s for SDUS and 105.94 cm/s for TOUS ($p < 0.001$). The average SDs were 23.0 cm/s for SDUS and 14.0 cm/s for TOUS ($p < 0.005$) (Table 1).

	SDUS Mean (cm/s)	SDUS SD (cm/s)	TOUS Mean (cm/s)	TOUS SD (cm/s)
Volunteer 1	128,1	12,7	105,2	9,6
Volunteer 2	93,6	16,9	83,2	12,8
Volunteer 3	169,8	20,2	112,4	17,1
Volunteer 4	214,6	18,2	123,0	12,9
Average	151,5	17,0	105,9	13,1

Table 1: Mean peak velocity measurements along with standard deviations.

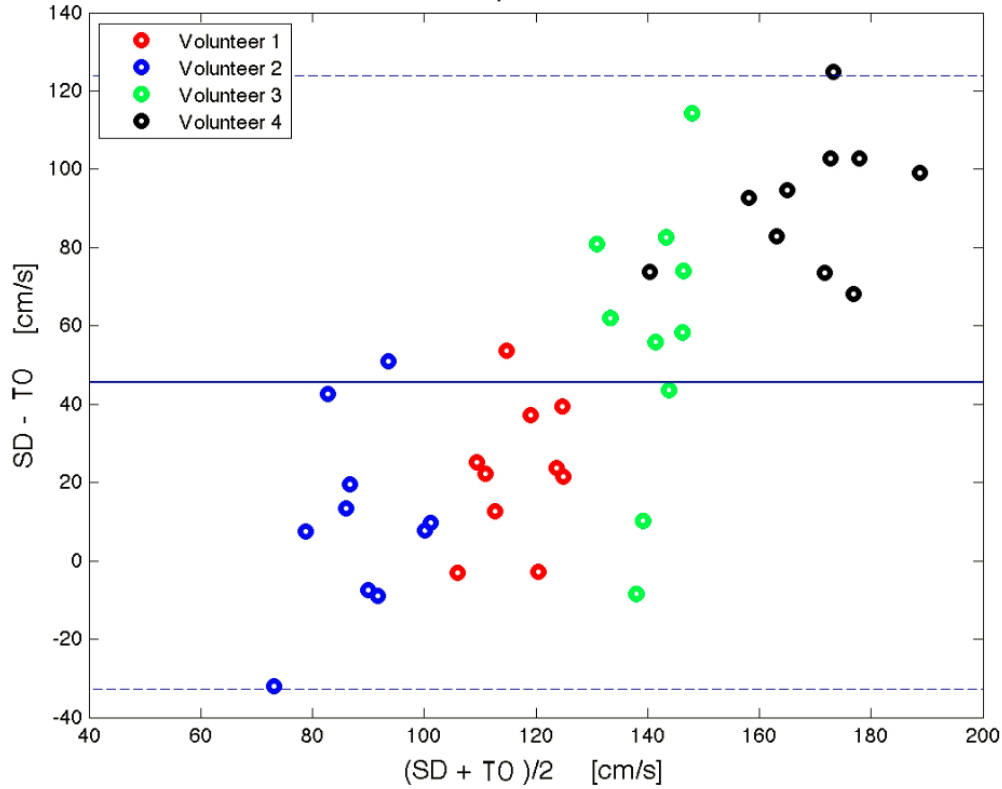


Figure 3: Bland-Altman plot with mean difference of 45.56 cm/s and limits of agreement from -32.83 to 123.96 for TOUS and SDUS.

4. NEW OR BREAKTHROUGH WORK TO BE PRESENTED

TOUS implemented on a commercial US scanner estimated venous velocities, and the vector velocity estimates were compared to estimates obtained with SDUS.

5. DISCUSSION AND CONCLUSION

The study demonstrated that TOUS performed better than SDUS for recording velocities in the veins of the lower limbs. The mean of the TOUS peak velocities had a significantly lower mean than the corresponding SDUS estimates (Tabel 1). The higher SDUS mean may indicate that the SDUS method overestimates the peak velocity.

The measurement of the peak velocity in veins by SDUS has limitations due to spectral broadening which may cause overestimation of the estimate²⁹. Studies have indicated that TOUS underestimates flow velocities^{19-21,30,31}. Nevertheless, the lower standard deviation of TOUS compared to SDUS suggests that TOUS is more precise than SDUS, which is in accordance with a previous study concerning blood flow estimation in the carotid artery²¹.

In this study, the difference in peak velocity increases with higher velocities (Fig. 3). A recent study showed likewise that the underestimation of flow velocities increases with increasing velocities in flowrig and in the ascending aorta. For this, a compensation scheme was proposed, which could be applied for TOUS estimation of venous flow as well (32).

Various advantages of TOUS have been demonstrated i.e. peak velocity measurements with little variation, volume flow measurements and visualization of complex flow patterns. However, it has also been shown that TOUS underestimates peak velocities and volume flow compared to other techniques.

In this study, it is demonstrated that TOUS underestimated the peak systolic velocity (PSV) when compared to PSV measurements obtained with SDUS, which is in accordance with previously published work. Pedersen et al. found that the PSV in the carotid artery was underestimated by 8% with TOUS compared to SDUS²¹. In the study by Hansen et al., regarding the ascending aorta, it was demonstrated that TOUS underestimate the PSV when compared to transesophageal echocardiography (TEE) by 22.9% and the volume flow by up to 43.8% when compared to pulmonary artery catheter thermodilution (32). Hansen et al. concluded that TOUS velocity measurements are useful, but TOUS volume flow measurements of large vessels with complex flow are not reliably estimated with 2D TOUS (32).

Volume flow measurements with TOUS have also been demonstrated and validated in arteriovenous dialysis fistulas. Hansen et al. examined arteriovenous dialysis fistulas in patients with TOUS and the ultrasound dilution technique (UDT). It was found that TOUS underestimated velocities by 30-40% depending on the calculation technique¹⁹. Brandt et al. did similar measurements on arteriovenous dialysis fistulas and found that TOUS underestimated the volume flow by 26% compared to UDT³². In both studies, the TOUS measurements had a lower standard deviation when compared to UDT^{19,32}.

Hansen et al. has demonstrated that the TOUS technique can be used for evaluation of the flow in the heart by intraoperative epicardial scanning. In a study it was demonstrated that TOUS can visualize complex flow patterns and that the technique may be used to distinguish between healthy and diseased aortic valves with qualitative and quantitative measures³³. With the TOUS technique, flow alterations can be graded by recording the flow complexity with measurements of vector angle diversity²⁰. In future studies the complex flow patterns in relation to the valves in the veins of the lower limbs will be characterized, and flow alterations will be graded with TOUS as proposed previously (18).

The results of this article support the results of these previous papers regarding the fact, that there is less variance in consecutive recordings with TOUS when compared to other techniques i.e. SDUS and UDT^{19-21,32-35}.

Velocity measurements obtained with SDUS are associated with uncertainty, because of various causes, and are primarily used to demonstrate the direction and duration of the flow in the veins of the lower limbs instead of an actual quantification⁴. The flow in the common femoral veins, external iliac vein, internal iliac vein and inferior vena cava are routinely examined in situations, where an occlusion in the pelvis or abdomen is suspected. The velocities of the veins on each side are compared and if discrepancies are present, an occlusion can be present. A constant flow in the common femoral vein indicates a proximal occlusion i.e. in the pelvis or abdomen, as the pulses from the respiratory and cardiac motions do not reach the examined vein.

A peak vein velocity (PVV) ratio (Eq. 1) has been proposed by Labropoulos et al. for characterizing venous stenosis. It has been suggested that a PPV-ratio of 2.5 across a venous stenosis require further examination by other modalities e.g. CTV, MRV and phlebography. However, PPV-ratios are not routinely measured in the evaluation of the veins in the lower limbs because of few studies in this area and because surgical or intravenous intervention rarely are performed due to venous obstructions⁶.

$$PVV \text{ ratio} = \frac{\text{Poststenotic peak vein velocity}}{\text{Prestenotic peak vein velocity}} \quad (1)$$

Nevertheless, PVV-ratios can easily be achieved with TOUS, as all velocities in the image plane are available simultaneously making it possible to perform multi-gating and instantaneous velocity ratios pre- and poststenotic as shown previously³³.

A recent study has shown that velocity measurements, done with Doppler US, were able to discriminate between a group of patients with mild venous insufficiency and a group of patients with advanced venous insufficiency. Peak retrograde velocities were recorded in sections of the veins where valvular incompetence and reflux were present, demonstrating the potential for more precise velocity measurements in the evaluation of patients with venous disorders ²⁴.

5.1 Limitations

The study is limited by the small number of participating volunteers of only one sex and by the fact that the popliteal vein has near optimal conditions for evaluation of velocity with SDUS. This means that the advantage of TOUS is not demonstrated in the greatest possible degree. When evaluating the femoral vein, the common femoral vein and the superficial veins the advantages of TOUS may become more obvious, because of the more parallel course of these veins in relation to the surface of the skin, which will challenge SDUS measurements as an acceptable insonation angle is difficult to achieve without compression of the examined vein.

5.2 Conclusion

The study indicates that TOUS estimates lower peak velocity with improved standard deviation when compared to SDUS. TOUS is an angle independent and real time blood vector velocity method, which can provide precise peak velocity measurements of the antegrade flow in the veins of the lower limbs. Flow alterations and complex flow patterns are not achievable with conventional Doppler US and might, as well as the peak velocities, be of value in evaluation of venous disease of the lower limbs.

The authors of this article are planning a study on a larger population, in which patients will have antegrade velocity measurements done in the popliteal vein as well as in the femoral vein in the mid-thigh region. Because the femoral vein has a location which is parallel to the surface of the skin, it is expected that the antegrade velocity measurements will be more precise with TOUS when compared to SDUS.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

- [1] Lattimer, C.R., "CVD: a condition of underestimated severity," *Int. Angiol.* 33(3), 222-8 (2014).
- [2] Seager, M.J., Busuttil, A., Dharmarajah, B., Davies, A.H., "Editor's Choice - A Systematic Review of Endovenous Stenting in Chronic Venous Disease Secondary to Iliac Vein Obstruction," *Eur. J. Vasc. Endovasc. Surg.* 51(1), 100-20 (2016).
- [3] Eklof, B., Perrin, M., Delis, K.T., Rutherford, R.B., Gloviczki P., "Updated terminology of chronic venous disorders: the VEIN-TERM transatlantic interdisciplinary consensus document," *J. Vasc. Surg.* 49(2), 498-501 (2009).
- [4] Wittens, C., Davies, A.H., Baekgaard, N., et al., "Editor's Choice - Management of Chronic Venous Disease: Clinical Practice Guidelines of the European Society for Vascular Surgery (ESVS)," *Eur. J. Vasc. Endovasc. Surg.* 49(6), 678-737 (2015).
- [5] Khilnani, N.M., "Duplex ultrasound evaluation of patients with chronic venous disease of the lower extremities," *AJR Am. J. Roentgenol.* 202(3), 633-42 (2014).
- [6] Labropoulos, N., Borge, M., Pierce, K., Pappas, P.J., "Criteria for defining significant central vein stenosis with duplex ultrasound," *J. Vasc. Surg.* 46(1), 101-7 (2007).
- [7] Rosales, A., Sandbaek, G., "Haemodynamics and catheter-based imaging in the diagnosis of venous disease. An interventional targeted approach," *Phlebology* 28(1), 162-8 (2013).
- [8] Arnoldussen, C.W., de Graaf, R., Wittens, C.H., de Haan, M.W., "Value of magnetic resonance venography and computed tomographic venography in lower extremity chronic venous disease," *Phlebology* 28(1), 169-75 (2013).
- [9] Mantoni, M., Larsen, L., Lund, J.O., et al., "Evaluation of chronic venous disease in the lower limbs: comparison of five diagnostic methods," *Br. J. Radiol.* 75(895): 578-83 (2002).

- [10] Hartung, O., Benmiloud, F., Barthelemy, P., Dubuc, M., Boufi, M., Alimi, Y.S., "Late results of surgical venous thrombectomy with ilio caval stenting," *J. Vasc. Surg.* 47(2), 381-7 (2008).
- [11] Hurst, D.R., Forauer, A.R., Bloom, J.R., Greenfield, L.J., Wakefield, T.W., Williams, D.M., "Diagnosis and endovascular treatment of ilio caval compression syndrome," *J. Vasc. Surg.* 34(1), 106-13 (2001).
- [12] Neglen, P., Raju, S., "Intravascular ultrasound scan evaluation of the obstructed vein," *J. Vasc. Surg.* 35(4), 694-700 (2002).
- [13] Baldt, M.M., Bohler, K., Zontsich, T., et al., "Preoperative imaging of lower extremity varicose veins: color coded duplex sonography or venography," *J. Ultrasound Med.* 15(2): 143-54 (1996).
- [14] Meyer, T., Cavallaro, A., Lang, W., "Duplex ultrasonography in the diagnosis of incompetent Cockett veins," *Eur. J. Ultrasound* 11(3), 175-80 (2000).
- [15] De Maeseneer, M., Pichot, O., Cavezzi, A., et al., "Duplex ultrasound investigation of the veins of the lower limbs after treatment for varicose veins - UIP consensus document," *Eur. J. Vasc. Endovasc. Surg.* 42(1), 89-102 (2011).
- [16] Coleridge-Smith, P., Labropoulos, N., Partsch, H., Myers, K., Nicolaides, A., Cavezzi, A., "Duplex ultrasound investigation of the veins in chronic venous disease of the lower limbs--UIP consensus document part I: basic principles," *Rev. Port. Cir. Cardiorac. Vasc.* 14(1), 53-60 (2007).
- [17] Jensen, J.A., Munk, P., "A new method for estimation of velocity vectors," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 45(3), 837-51 (1998).
- [18] Munk, P., Jensen, J.A., "A new approach for the estimation of the axial velocity using ultrasound," *Ultrasonics* 37(10), 661-5 (2000).
- [19] Hansen, P.M., Olesen, J.B., Pihl, M.J., et al., "Volume flow in arteriovenous fistulas using vector velocity ultrasound," *Ultrasound Med. Biol.* 40(11), 2707-14 (2014).
- [20] Hansen, K.L., Moller-Sorensen, H., Pedersen, M.M., et al., "First report on intraoperative vector flow imaging of the heart among patients with healthy and diseased aortic valves," *Ultrasonics* 56, 243-50 (2015).
- [21] Pedersen, M.M., Pihl, M.J., Haugaard, P., et al., "Comparison of real-time in vivo spectral and vector velocity estimation," *Ultrasound Med. Biol.* 38(1), 145-51 (2012).
- [22] Brandt, A.H., Hansen, K.L., Nielsen, M.B., Jensen, J.A., "Velocity estimation of the main portal vein with Transverse Oscillation," *Proc. IEEE Ultrason. Symp.*, 1-4 (2015).
- [23] Hansen, K.L., Udesen, J., Gran, F., Jensen, J.A., Nielsen, M.B., "In-vivo examples of flow patterns with the fast vector velocity ultrasound method," *Ultraschall Med.* 30(5), 471-7 (2009).
- [24] Konoeda, H., Yamaki, T., Hamahata, A., Ochi, M., Sakurai, H., "Quantification of superficial venous reflux by duplex ultrasound-role of reflux velocity in the assessment the clinical stage of chronic venous insufficiency," *Ann. Vasc. Dis.* 7(4), 376-82 (2014).
- [25] van Bemmelen, P.S., Bedford, G., Beach, K., Strandness, D.E., "Quantitative segmental evaluation of venous valvular reflux with duplex ultrasound scanning," *J. Vasc. Surg.* 10(4), 425-31 (1989).
- [26] Broholm, R., Kreiner, S., Baekgaard, N., Jensen L.P., Sillesen H., "Observer agreement of lower limb venous reflux assessed by duplex ultrasound scanning using manual and pneumatic cuff compression in patients with chronic venous disease and controls," *Eur. J. Vasc. Endovasc. Surg.* 41(5), 704-10 (2011).
- [27] Hansen, K.L., Pedersen, M.M., Jensen, J.A., Nielsen, M.B., "Doppler ultrasonography of the abdomen," *Ugeskr. Læger* 173(47), 3016-9 (2011).
- [28] Eberhardt, R.T., Raffetto, J.D., "Chronic venous insufficiency," *Circulation* 130(4), 333-46 (2014).
- [29] Tortoli, P., Lenge, M., Righi, D., Ciuti, G., Liebgott, H., Ricci, S., "Comparison of carotid artery blood velocity measurements by vector and standard Doppler approaches," *Ultrasound Med. Biol.* 41(5), 1354-62 (2015).
- [30] Udesen, J., Jensen, J.A., "Investigation of transverse oscillation method" *IEEE Ultrason. Ferroelectr. Freq. Control* 53(5), 959-71 (2006).
- [31] Hansen, K.L., Udesen, J., Thomsen, C., Jensen, J.A., Nielsen, M.B., "In vivo validation of a blood vector velocity estimator with MR angiography," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 56(1), 91-100 (2009).
- [32] Brandt, A.H., Olesen, J.B., Hansen, K.L., Rix, M., Jensen, J.A., Nielsen, M.B., "Surveillance of hemodialysis vascular access with ultrasound vector flow imaging," *Proc. SPIE* (9419), (2015).
- [33] Hansen, K.L., Pedersen, M.M., Moller-Sorensen, H., et al., "Intraoperative cardiac ultrasound examination using vector flow imaging," *Ultrason. Imaging* 35(4), 318-32 (2013).
- [34] Hansen, K.L., "In-vivo studies of new vector velocity and adaptive spectral estimators in medical ultrasound," *Dan. Med. Bull.* 57(5), 1-23 (2010).
- [35] Hansen, K.L., Moller-Sorensen, H., Kjaergaard, J., et al., "Vector Flow Imaging Compared with Conventional Doppler Ultrasound and Thermodilution for Estimation of Blood Flow in the Ascending Aorta," *Ultrason. Imaging*, Epub. 1-16 (2015).